Complex Dielectric Properties of the Sapwoods of Aspen, White Birch, Yellow Birch and Sugar Maple

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Abstract

This study presents the dielectric properties as a function of moisture content, temperature, and microwave frequency variation, for four hardwood species. These properties were measured using the cavity perturbation technique at frequencies between 0.4 and 2.47 GHz. We varied the wood temperature from -20 to 58 ºC and moisture content from 40 to 136% depending on species. Dielectric constant, loss factor, loss tangent and penetration depth varied with species, moisture content, and microwave frequency. The patterns of variation were established for the studied species and any discrepancies are discussed, namely concerning their implication when used in wood industry (non-destructive testing, heating and drying).

Keywords: Dielectric properties, Moisture content, Microwave frequency, Drying, Wood

Background

Microwave energy is used commercially for a number of applications such as cereal and granola baking, drying of coatings, snack food processing, foundry core drying, pharmaceutical processing, ceramic filter drying, ceramic sintering, rubber vulcanization, chemical vapour deposition, mold drying, and chemical waste processing. However, use of microwave energy is not so common in the wood products industry [1]. TrusJoist, a Weyerhaeuser company, consolidates veneer cut strands into processed composite lumber applying microwave energy [1]. Another application where the microwave processing of wood might be commercialized is the sanitization of wood to eradicate exotic pest infestations in lumber. It may provide a useful tool to exclude these invasive pests from crossing the borders in wood pallets and crates or other forms of solid wood packing material. Currently, heat treatment and methyl bromide fumigation are the only two sanitization treatments internationally approved for solid wood packing materials [2]. However, the U.N. phytosanitary commission and the USDA are seeking alternative technologies, such as microwave energy, which can be used for this application [3]. Fleming et al. [4, 5] showed that microwave treatment of wood (2.45 GHz) eradicated cerambycid larvae and the cottonwood borer beetle (CWB), *Plectrodera scalator* (Fabricius) (Coleoptera: Cerambycidae) in laboratory-size wood samples.

Microwave processing of wood involves several complicated physical phenomena. It includes absorption of the electromagnetic energy, transport of the generated heat, transport of water through the wood and changes in wood dimensions through shrinkage. For efficient wood processing through microwave energy, one needs to understand these various phenomena. The values and variation of wood dielectric properties contribute to the understanding of molecular structure of wood and wood-water interaction.

The dielectric properties of wood have been studied in the past using different techniques and a wide range of frequencies [6-16]. Methods of measuring wood dielectric properties include slotted wave guide and standing wave ratio meter, resistance-capacitance bridge with a tuned null detector, test capacitor assembly, transmission/reflection method and open-ended coaxial probe.

For proper equipment design and efficient processing of materials such as wood, their dielectric properties must be known (Equations 1 to 7). The frequency-dependent relative dielectric constant, ε(f)*, determines the interaction between wood and the microwave electromagnetic field. This parameter determines the behaviour of a material in an electric field and is constituted of two components (Equation 1), usually written as a complex number. The “real” component, ε’, the relative permittivity, often called the dielectric constant, represents the ability of a material to be electrically polarized by an applied electric field. The second component, the “imaginary” component, ε", is referred to as the loss factor, and is used to calculate the amount of electromagnetic energy converted into heat. The loss tangent is defined as the ratio of the loss factor to the dielectric constant (Equation 2), and is a useful measure of how well microwave energy is absorbed.

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \qquad [1]$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad [2]$$

The average power absorbed per unit volume in a material (P_{abs}) at a location "z" can be calculated if one knows the peak electric field, $E_p(z)$, in the material, using equation 3.

$$P_{abs} = \tfrac{1}{2}\omega \cdot \varepsilon_0 \cdot \varepsilon'' \cdot Ep^2 \qquad [3]$$

where;

ω = angular frequency (ω=2πf);

ε_0 = free space dielectric constant (8,854x10^{12} Farads/m);

$E_p(z)$ = peak temporal value of the electric field (V/m) at position z.

When an electromagnetic wave is vertically incident ("z" direction) on a surface of a material, part of the wave is reflected and part penetrates into the material and propagates through the material. The energy in this transmitted wave is gradually absorbed by the material (converted to heat) as the wave penetrates deeper, and the wave energy content is thus reduced with depth into the material. The power carried by this transmitted wave decreases exponentially and can be calculated according to the following equation (4) :

$$P_{trans}(z) = P_{trans}(z=0) * e^{-2*\alpha*z} \qquad [4]$$

Where

$P_{trans}(z)$ - Power in the travelling transmitted (W/m^2);

$P_{trans}(z = 0)$ - Power just inside the material surface in the "normal" direction z (W/m^2);

z - Distance from the surface of the material (m).

α - Attenuation constant, (1/metres);

The attenuation constant is a measure of the rate of absorption of the wave power into the material. This constant is determined according to equation 5.

$$\alpha = \frac{2\times\pi\times f}{2{,}998\times10^{8}}\times\sqrt{\frac{\varepsilon^{'}}{2}\left[\sqrt{(1+(\tan\delta)^{2})}-1\right]} \quad \text{(metres)}^{-1} \qquad [5]$$

The *Penetration Depth (d_p)* is the distance into the material at which the power in the transmitted wave is reduced to 1/e the incident power – meaning ~ 63% of the initial power has been deposited as heat by the time the wave gets to this depth. The penetration depth is given by equation 6.

$$d_p = \frac{1}{(2\alpha)} \qquad [6]$$

It is well known that the complex dielectric properties are frequency and temperature dependent. They were reported for a wide range of inorganic and organic materials in the frequency and temperature ranging from 100 to 10^{10} Hz and –12°C to 200°C, respectively [17], for agricultural products [18] and wood and its products [6-16, 19-21]. Torgovnikov [21] brought together a large amount of information on the dielectric properties of wood and wood-based products.

The dielectric properties of wood varied with different factors related to the wood itself and to the frequency of the microwave application. Available studies reported consistent trends in the variation of dielectric properties with microwave frequency. The common trend is that the dielectric constant decreases with frequency, while the loss tangent increases with frequency [6, 10-11, 13-14, 22-23].

The dielectric properties of wood are also moisture content dependent. The presence of water produces strong dipole moments and increases the effective loss factor, making it a good candidate for processing with high frequency energy [24, 25]. Because application of heat causes changes in moisture content, the variation of ε’’ with moisture content is important. Bound water is tightly held and less rotationally free than the free water present in various cavities. Thus, the latter makes higher dielectric losses possible [24]. A few other studies reached the same conclusion regarding the variation of the dielectric properties with moisture content [6-16, 19-24, 27-28]. Note however that the non-zero loss factor for dry wood, together with a complex system of standing waves (the sample size and the wave length are usually of the same order of magnitude) eventually turn into thermal runaway when the power continue to be applied to dry parts of wood [25].

Each material has different curve forms for different frequency ranges. Further, the slopes of ε' and ε'' versus moisture content curve are critical to industrial applications where moisture leveling of a material, especially in sheet form, is the main objective [24]. It is commonly said that wetter parts of a material absorb more power and tend to level off at an initially uneven moisture distribution. However, equation [3] tells us that two main factors are involved in the volumetric power : ε'' and *Ep*. At high moisture contents, ε'' is high, but *Ep* may be small, due to a high value of ε'. Both effects are opposing, which might result in a low power density at high moisture content. Figure 1 depicts this effect in the case of a Radio Frequency heating. At low moisture content, the power density is low due to an opposite situation: although the electrical field is important because of the small value of ε', the loss factor, which dramatically reduces at low moisture contents, explains why the power is low. In this case of Radio Frequency heating, the maximum power density is obtained at an average moisture content, close to 30%, which represents the best compromise between the electrical field and the loss factor [26]:

- above this critical value, the power is supplied preferentially to the less wet boards, which tends to increase the moisture content differences,
- below this critical value, moisture leveling by dielectric heating becomes effective. This leveling effect is however less effective if ε'' becomes almost independent of moisture content [24].

Variations in wood density always exist between and within species. This variation might have significant impact on the dielectric properties of the wood. To consider such complex interactions, look up tables, exemplified by those of Torgovnikov [21], may be constructed and used for specific calculations [24]. Available reports on the impact of wood density on the dielectric properties of wood are contradictory. Some reported that the dielectric properties of the wood varied with density [21, 27-28] while others reported no significant variation of the dielectric properties with wood density [6]. In the latter case, these results could be explained by the narrow range of studied densities and by the similarity in the wood structure of the tested species [6].

The anisotropy of wood influences also the dielectric properties of wood [11, 21, 24 - 2527]. The optimum field orientation in a microwave applicator may be deduced from the ε'' versus moisture content curves as losses are higher for the field orientation parallel to the grain [24]. The dielectric constant and the loss factor of the wood for a given moisture content were higher in the longitudinal direction [27]. However, for three eastern species the structural direction did not show any significant effect on the dielectric properties [6].

This introduction pointed out the importance of the complex dieletric properties (the dielectric constant and the loss factor) to understand and model dielectric heating: The objectives of this study were to study the variation of complex dielectric properties of four eastern Canadian hardwoods with moisture content, temperature and frequency.

Experimental

We measured the dielectric properties on increment core samples taken in winter from fresh logs of four different species: aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera*), yellow birch (*Betula alleghaniensis*) and sugar maple (*Acer saccharum*). All were long, slim cylindrical samples taken from sapwood in the longitudinal direction of the wood. Samples were immediately wrapped after they were extracted and kept frozen until measurement. All measurements of the dielectric properties were done with the microwave electric field parallel to the longitudinal axis of the sample.

The system and method we used for measuring the dielectric properties of wood is based on the cavity perturbation technique, and can measure the complex scalar permittivity at frequencies between 50 MHz and 3 GHz, and up to a temperature of 1400 °C [29]. The system is suitable for measurements on most classes of materials, including biological materials, such as wood and measures the complex dielectric constant of materials during conventional heating, curing or sintering. The principles and detailed methods for measurements, calibration and data analysis with this system are detailed in previous reports [29-31]. For the present study, sample preparation, calibration techniques, and data analysis methods were tailored to the properties of the specific wood samples, and the actual sequence of temperature versus time for the measurements is governed by the wood properties and its ultimate application.

In the present case, both the relative moisture content and the density of each sample had to be known, both at the beginning and end of each measurement run. This required careful mass and sample dimension measurements at all stages, and also required a final baking of each sample to determine the oven-dry weight (obtained after drying at 103°C for 24 hours). Samples tested were 5.5 mm in diameter and 20 mm long. In order to avoid contamination of the wood samples, handling and inserting the samples into the sample holder was always done with tweezers. The initial dimensions and the initial mass of each sample were determined immediately before each run. Each run consisted of starting at room temperature, and increasing the sample temperature by steps of 10°C, and holding after each step for 6 minutes to allow the temperature in the sample to stabilize and become uniform. Table 1 summarizes the range of moisture content and density per species measured in this study. The dielectric properties at 0% moisture content were measured for aspen only.

For measurements of wood samples in the frozen state, two samples from each species were frozen in a freezer (-22 ±2°C) before measurements. When the apparatus was ready for measurements, each sample was retrieved from the freezer, unwrapped, quickly weighed, and immediately measured. The measurements were then continued every 5 to 10 minutes until the material reached room temperature. The sample was then weighed again, and the measurement sequence to 58 °C done. At the end of each run, the sample was dumped out of the holder and the empty holder was re-measured, and the final sample mass and dimensions determined and the moisture content values were attributed to all previous measurements.

This method determines the real and imaginary parts of the complex dielectric constant, denoted by ε' and ε''. Three quantities are derived using these numbers – the loss tangent ($\tan\delta$), the electric field attenuation constant (α) and the penetration depth (d_p).

Results and discussion

The dielectric properties of the four studied species as a function of moisture content and microwave frequency at a constant temperature of 24 °C are presented in Table 1. The variation of the dielectric properties with wood temperature at constant moisture content per species is shown in Table 2. The results are also graphically presented to describe the effects of frequency, wood species, wood moisture content, and wood initial temperature on the dielectric properties of aspen, white birch, yellow birch and sugar maple.

Variation of the dielectric properties with wood moisture content

The variation of the dielectric constant with moisture at a frequency of 2.47 GHz is depicted in Figure 2. In agreement with previous studies [6; 10-11; 19-23], the dielectric constant increases with increasing moisture content. The dielectric constant for all species follows the same relationship, indicating that the variation in wood structure and density for the studied species did not have significant impact on the dielectric constant at higher moisture contents. This conclusion is similar to that reached for three eastern softwoods [6]. The variation pattern of the dielectric constant with moisture content was the same for the 5 microwave frequencies (Figure 2). Despite the slight dispersion among the five studied frequencies, all experimental points fall almost on the same curve as shown in Figure 3.

Data from Figure 4 shows the variation of the loss factor with wood moisture content at a frequency of 2.47 GHz. In agreement with previous studies [6, 20-21, 24], the loss factor increased with increasing moisture content. Similar to the dielectric constant, the variation of the loss factor with moisture content for the four studied species fall almost on the same relation (Figure 4). However, compared to the dielectric constant, a slight dispersion is observed at high moisture content values.

The pattern of variation of the loss factor with moisture content (Figure 5) was the same for the five studied frequencies and is characterized by a steady increase followed by leveling off beyond 100% moisture content. At any given moisture content, the loss factor increases with increasing microwave frequency.

The pattern of variation in the loss tangent with moisture content at a frequency of 2.47 GHz is shown in Figure 6. For the four species studied, the loss tangent showed an initial increase form 0% moisture content to reach a maximum around 40-60% followed by a constant decrease with increasing moisture content after this point. The pattern of variation was typical for the four studied species. This pattern of variation is in agreement with previous studies [10, 28], which reported that the loss tangent increased initially with moisture content to reach a maximum around 60% moisture content and then decreased linearly.

The variation of loss tangent among wood species can be explained by the variation in wood density [23]. At any given moisture content, the higher the wood density, the higher is the loss tangent. From the data in Figure 6, the same conclusion could be reached except that for aspen the measured loss tangent was higher than that of the other three species, despite its lower density. One plausible explanation for this result is non-uniformity of moisture content within the wood sample.

The general pattern of variation of the loss tangent with microwave frequency is shown in Figure 7. Generally, the higher the frequency, the lower is the loss tangent.

No specific pattern of variation in penetration with moisture content was found, as shown in Figure 8 for the 2.47 MHz frequency. However, the depth of penetration depended on microwave frequency as shown for aspen (Figure 9). Although there was no general pattern of variation in penetration depth with moisture constant, clear differences are found between the different frequencies – the higher the frequency, the lower the penetration depth at any moisture constant. This result is consistent for the four studied species (Table 1).

Variation of the dielectric properties with initial wood temperature

The variations of the dielectric constant with temperature at a constant microwave frequency and for a single species at various microwave frequencies are shown in Figures 10 and 11, respectively. The dielectric constant increases from the frozen state to reach a maximum around 25 °C, followed by a decrease at higher temperatures. This pattern of variation is found for the four studied species (Figure 10) and all microwave frequencies (Figure 11). Data from Figure 10 and Table 2 show significant variations between the studied species. These variations could be explained by the differences between wood densities of the studied species and also between the initial moisture contents of the samples. In agreement with previous reports [9-10, 27], it is important to note that the variation of the dielectric constant with temperature is much less important than its variation with moisture content.

The variations of the loss factor with wood temperature at a constant microwave frequency and for a single species at different frequencies are depicted in Figures 12 and 13, respectively. The general pattern of variation is characterized by a constant decrease of the loss factor with increasing wood temperature. In a previous report [20], the loss factor increased with increasing temperature. The trend of variation is contradictory to our results and could be explained by the high initial moisture contents of the wood samples we studied.

The loss factor varied with wood species (Figure 12) and this variation could be explained by variation in wood density and wood moisture content. This property also varied with microwave frequency. Higher frequency led to a higher loss factor at any given temperature (Figure 13).

The variation of the loss tangent with temperature is similar to the variation of the loss factor. For a constant frequency, the loss tangent decreased with increasing wood temperature for the four studied species (Figure 14). Similarly, the loss tangent decreased with increasing temperature for all studied frequencies (Figure 15) and species (Table 2).

No specific pattern of variation is found in penetration depth with increasing temperature at constant microwave frequencies and moisture contents (Figure 16), except in yellow birch, where it decreased with increasing temperature. The penetration depth decreased substantially with increasing microwave frequencies as shown in Figure 17. .

Practical implications of the results

The data presented here should be useful in designing microwave applicators for wood heat treatment such as the phytosanitary treatment of wooden packaging materials. In general the influence of moisture content and the microwave frequencies overshadowed the influence of species and the initial wood temperature. Thus, the present data could be used for approximate design calculations for the heat treatments of green wood for most common hardwoods used for the manufacture of pallets and packaging material. Because such a treatment has to be efficient for a wide range of moisture content levels, the knowledge of both the effect of temperature and moisture content on dielectric properties is of utmost important.

The non-significant variation of the dielectric constant and loss factor among wood species suggest that all species could be treated in the same applicator at the same time. This is of particular interest for several wood processes such as heat treatments to comply with the regulations of phytosanitary regulations and wood drying operations.

The apparently frozen material at –20 °C had a dielectric response that was larger than that of the room temperature wood. This is not the case in the comparison of ice and water, where the immobilization of the water molecule in the ice crystal structure dramatically reduces the molecule’s ability to move in response to the microwave electric field, thus reducing both the real part of the dielectric constant and the absorption of microwaves by the ice. The fact that the “frozen” material has roughly the same properties as the thawed material suggests that heating of the wood from a “frozen” state to 60°C can be done in the same applicator all in one pass !

The close relationship between wood moisture content and the dielectric constant (Figure 2), especially beyond the saturation point, could be used for the development of innovative non-destructive tools for the measurement of wood moisture content. Statistical linear models describing this relationship for single species or all species are presented in Table 4 and show high coefficients of determination between the dielectric properties measured and modeled values.

Conclusions

The following conclusions may be drawn relative to the dielectric properties of aspen, white birch, yellow birch and sugar maple when measured over a frequency range of 400 MHz to 2.47 GHz at moisture contents above the saturation point ranging from 40% to 136% and temperatures ranging from -20 °C to 58 °C. Results from the study led to the following conclusions:

1. At a constant temperature and microwave frequency, both the dielectric constant and the loss factor increased with increasing moisture content while the loss tangent decreased. The penetration depth did not show any significant variation with moisture content.
2. The dielectric constant did not show any significant variation with increasing microwave frequency while the loss factor showed an important increase with increasing frequency especially at high moisture contents. The loss tangent and the penetration depth were higher at lower microwave frequencies.
3. At constant microwave frequency and wood temperature, only the loss tangent showed significant variation with wood species.
4. Results from this study suggest that the dielectric properties of the wood could be used for precise determination of its moisture content.

References :

1. Fleming, M.R.; Janowiak, J. J; Kimmel, J.D.; Halbrendt, J.M. ; Bauer, L.S. ; Miller, D.L. ; Hoover, K. Efficacy of commercial microwave equipment for eradication of pine wood nematodes and cerambycid larvae infesting red pine. Forest Products Journal **2005**, 55 (12), 226-232.
2. Food and Agricultural Organization of the united Nations. Specifications for plant protection products: chlorsulfuron. Specifications. Document No. AGP:CP/371, **2000**.
3. USDA. Importation of Solid Wood packaging Material. Draft Environmental Impact Statement-October **2002**.
4. Fleming M.R.; Hoover, K.; Janowiak J. J.; Fang, Y.; Wang, X.; Liu W.; Wang, Y.; Hang, X.; Agrawal, D.K.; Mastro, V.C.; Lance, D.R.; Shield, J.E.; Roy, R. Microwave irradiation of wood packing material to destroy the Asian longhorned beetle Forest Products Journal **2003,** 53(1), 46-52.
5. Fleming M.R.; Janowiak J.J.; Kearns J; Shield J.E.; Roy R.; Agrawal D.K.; Bauer L.S.; Miller D.L.; Hoover K. Parameters for scale-up of lethal microwave treatment to eradicate cerambycid larvae infesting solid wood packaging materials. Forest Products Journal **2004**, 54(7/8), 80-84.
6. Afzal, M. T., Colpits, B., Galik, K. Dielectric Properties of Softwood Species Measured with an Open-ended Coaxial Probe. In proceedings 8th International IUFRO Wood Drying Conference, Brasvo, Romania, August, 24-29, **2003**; 110-115.

7. Dubey, Y.M.; Deorani, S.C. Dielectric properties of coniferous timbers at microwave frequencies. J. Ind. Acad. Wood Sci., **1995**, 26 -27 (1 -2), 77-82.
8. Jain, V.K.; and Dubey, Y.M. Dielectric constant of some Indian timbers in axial direction at microwave frequencies. J. of Ind. Acad. Wood Sci. **1988**, 19 (2), 25-36.
9. James, W.L. Dielectric properties of wood and hardboard. Variation with temperature, frequency, moisture content and grain direction. Res. Paper FPL-245, USDA Forest Service. Forest Prod. Lab., Madison, WI. 33 pages, **1975**.
10. James, W.L. Dielectric behavior of Douglas fir at various combinations of temperature, frequency, and moisture content. Forest Products Journal. **1977,** 27 (6), 44-48.
11. James, W.L.; Hamil, D.W. Dielectric properties of Douglas fir measured at microwave frequencies. Forest Prod. J. **1965**, 15 (2), 51-56.
12. Jarvis, J.; Vanzura, E.; Kissick, W. Improved technique for determining complex permittivity with the transmission/reflection method. IEEE Transactions on Microwave Theory and Techniques, **1990,** 38 (8), 1096-1103.
13. Kabir, M.F.; Khalid, K.B.; Daud, W.M.; Aziz, S.H.A. Dielectric properties of rubber wood at microwave frequencies measured with an open-ended coaxial line. Wood and Fiber Science, **1997**, 29 (4), 319-324.
14. Peyskens, E.; Poureq, M.; Stevens, M.; Schalck, J. 1984: Dielectric properties of softwood species at microwave frequencies. Wood Science and Technology, **1984**, 18 (1), 267-280.

15. Skaar, C. The dielectric properties of wood at several radio frequencies. Syracuse University. New York, **1948**.

16. Tinga, W. R. Dielectric properties of Douglas fir at 2.45 GHz. Journal of Microwave Power, **1969**, 4 (3), 162-164.

17. Von Hippel, A.R.: Dielectrics and waves. John Wiley, New York , 1959.

18. Nelson, S. Electrical properties of agricultural products - a critical review. Transactions of the American Society of Agricultural Engineers, **1973,**16(2), 384–400.

19. Hearmon, R.F.S. Burcham, J.N. The dielectric properties of wood. Her Majesty's Stationary Off. Sec. Pep. 8, London,1954.

20. Zhou, B., Avramidis, S. On the loss factor of wood during radio frequency heating. Wood Science and Technology, 1999, 33, 299-31.

21. Torgovnikov, G.I., Dielectric properties of wood and wood based materials. Springer Verlag Berlin, 1993.

22. Vermaas, H.; Pound, J.; and Borgin, K. The loss tangent of wood and its importance in dielectric heating. South African Forestry Journal, **1990**,1(89), 5-8.

23. James, W.L.; Yen, Y.-H.; King, R. J. A microwave method for measuring moisture content, density, and grain angle of wood. Research note FPL-0250, 1985.

24. Resch, H. High-Frequency Heating Combined With Vacuum Drying Of Wood. In proceedings 8th International IUFRO Wood Drying Conference, Brasvo, Romania, August, 24-29, **2003**; 127-132.

25. Perré P. and Turner I. W., Microwave drying of softwood in an oversized waveguide, AIChE Journal, 1999, 43**,** 2579-2595.

26. Bucki M. and Perré P., Physical formulation and numerical modeling of high frequency heating of wood, Drying Technology, 2003, 21, 1151-1172.

27. Daian, G.; Taube, B.; Birnboim, A.; Daian, M. Sharmkov, Y. Modeling the Dielectric Properties of Wood. Wood Science and Technology, 2006, 40, 237-246.

28. Antti L. Heating and Drying Wood using Microwave Power. Doctoral Thesis. Lulea University of Technology, Sweden. **1999**, 35.

29. Hutcheon, R.M.; de Jong, M.; Adams, F.P. A System for Rapid Measurements of RF and Microwave Properties Up to 1400 °C. Journal of Microwave power and Electromagnetic Energy, **1992**, 27(2), 93-102.

30. Adams, F.P., de Jong., Hutcheon R.M. Sample Shape Correction Factors for Cavity Perturbation Measurements, Journal of Microwave power and Electromagnetic Energy, **1992**, 27 (3), 131-135.

31. de Jong, M., Adams, F.P. Hutcheon, R. Computation of RF Fields for Applicator Design, Journal of Microwave power and Electromagnetic Energy, 1992, 27 (3), 136-142.

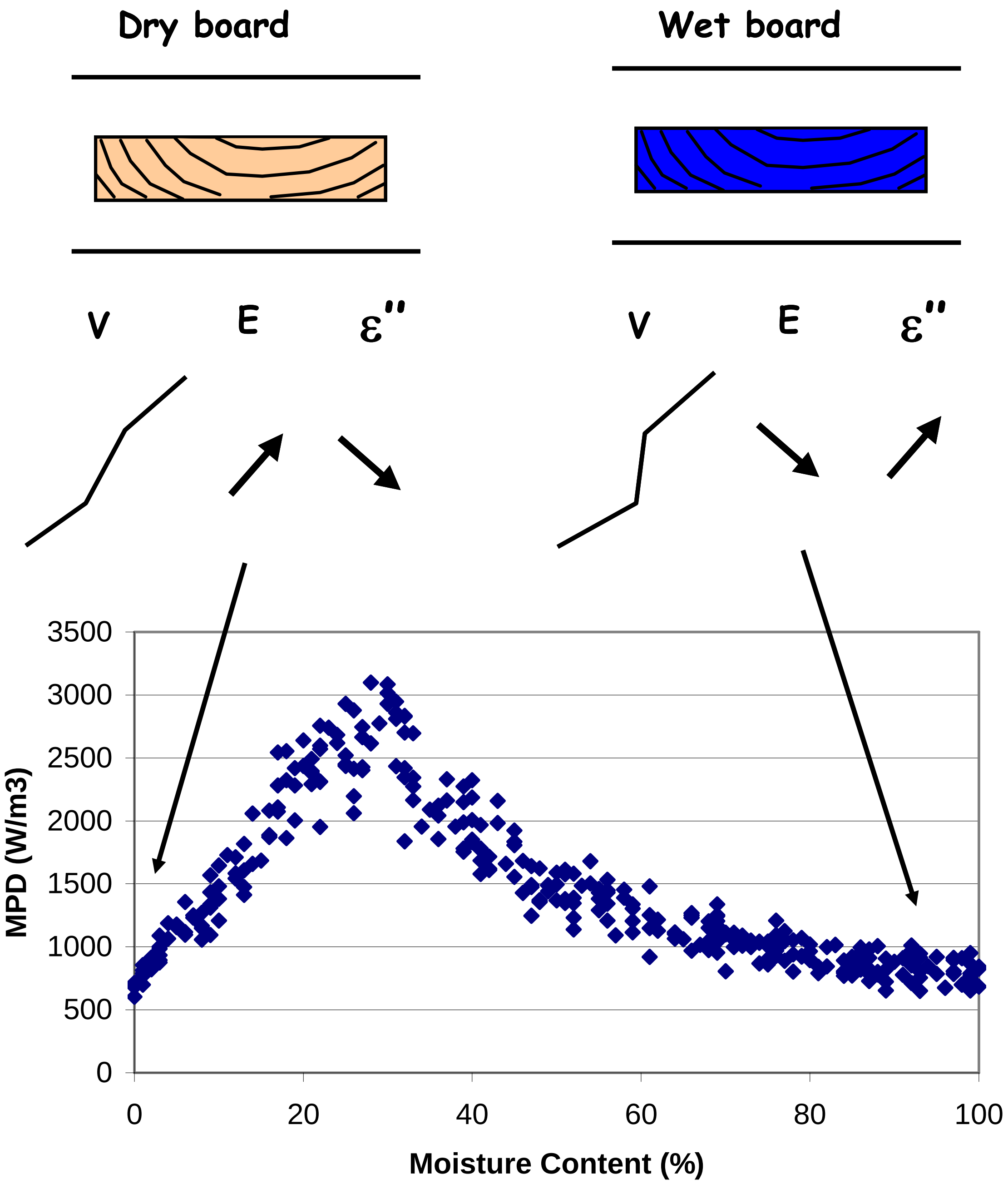

Figure 1: Mean Power Density of each single board as a function of Moisture Content computed for a stack of 8-boards : Radio-Frequency heating, 40 independent runs with stochastic variation of MC of each board. (adapted from [26]). The general trend of this plot has to be explained by the cumulative effect of ε' and ε''.

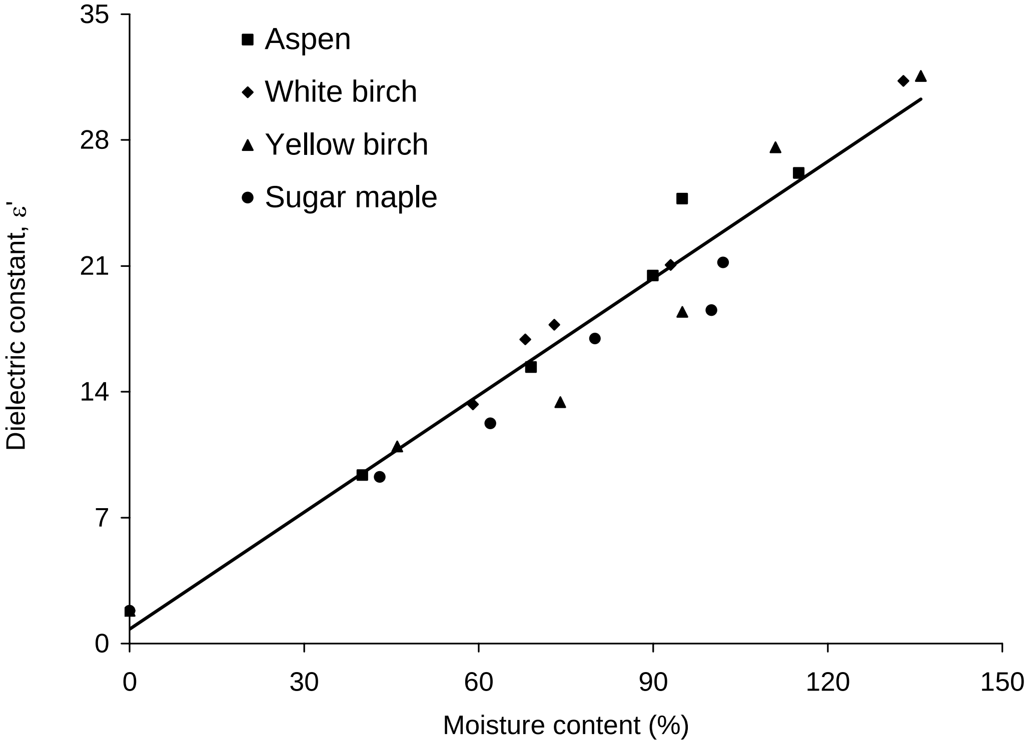

Figure 2: Variation of the dielectric constant of aspen, white birch, yellow birch and sugar maple as a function of moisture content, measured at constant temperature (25 °C) and frequency 2.47 (GHz).

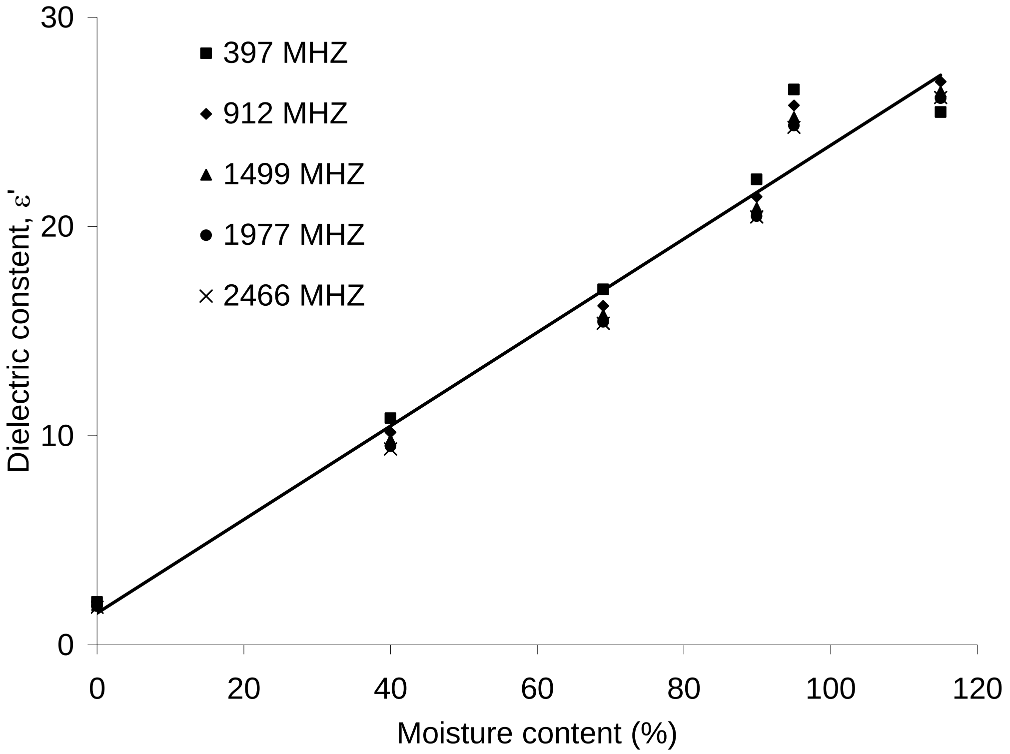

Figure 2: Variation of the dielectric constant measured at constant temperature (24 °C) for aspen as a function of moisture content and microwave frequency.

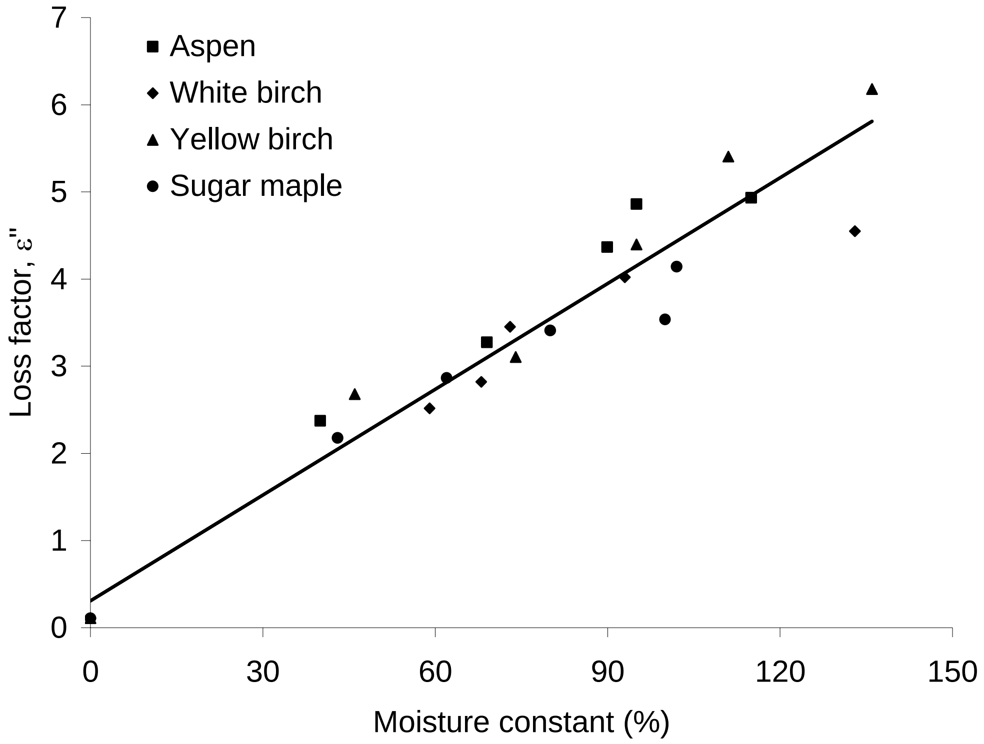

Figure 3: Variation of the loss factor (ε”) of aspen, white birch, yellow birch and sugar maple as a function of moisture content measured at constant temperature (25 °C) and frequency (2.47 GHz).

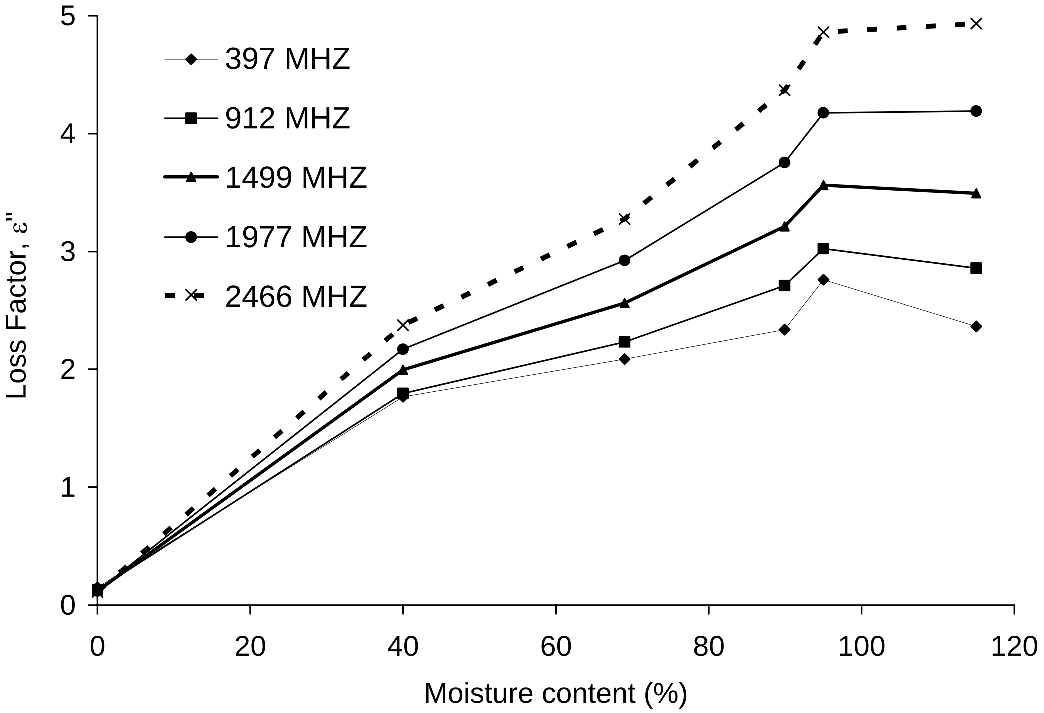

Figure 4: Variation of the loss factor (ε”) of aspen measured at constant temperature as a function of moisture content and microwave frequency.

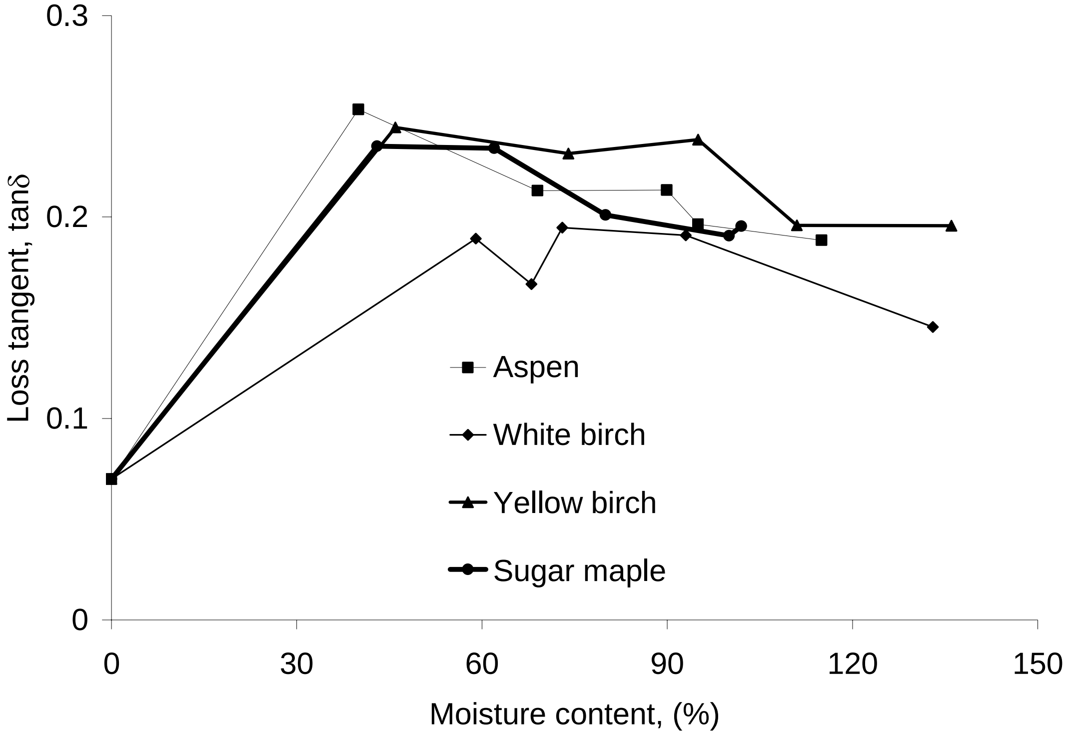

Figure 5: Variation of the loss tangent (tanδ) of aspen, white birch, yellow birch and sugar maple as a function of moisture content measured at constant temperature (25 °C) and frequency (2.47 GHz).

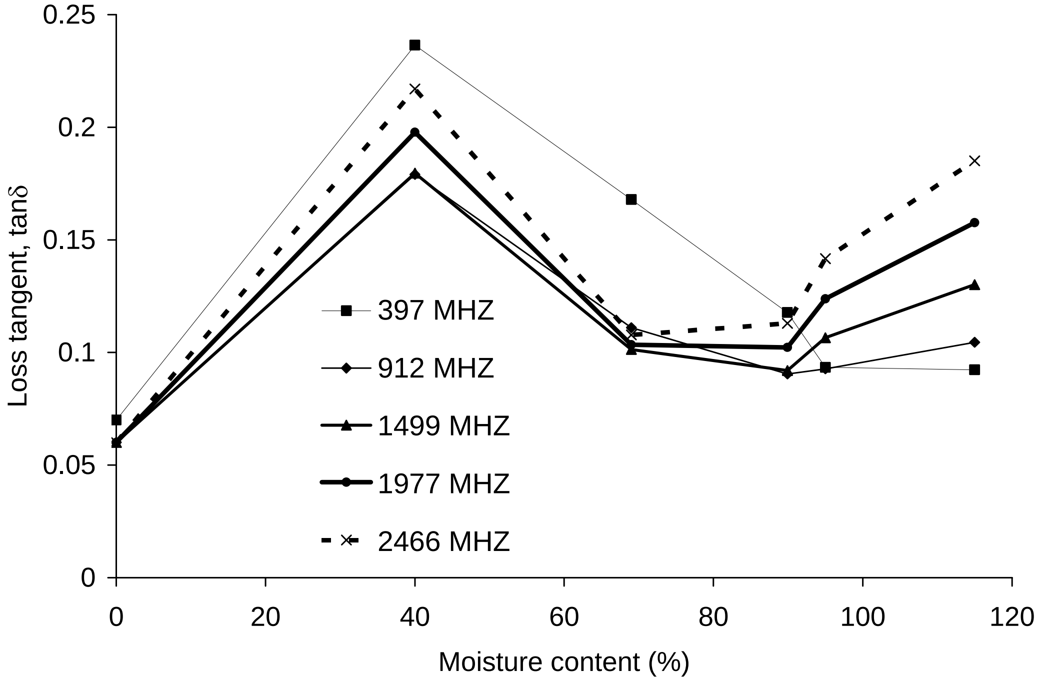

Figure 6: Variation of the loss tangent (tanδ) of aspen as a function of moisture content and microwave frequency at a constant temperature (24 °C)

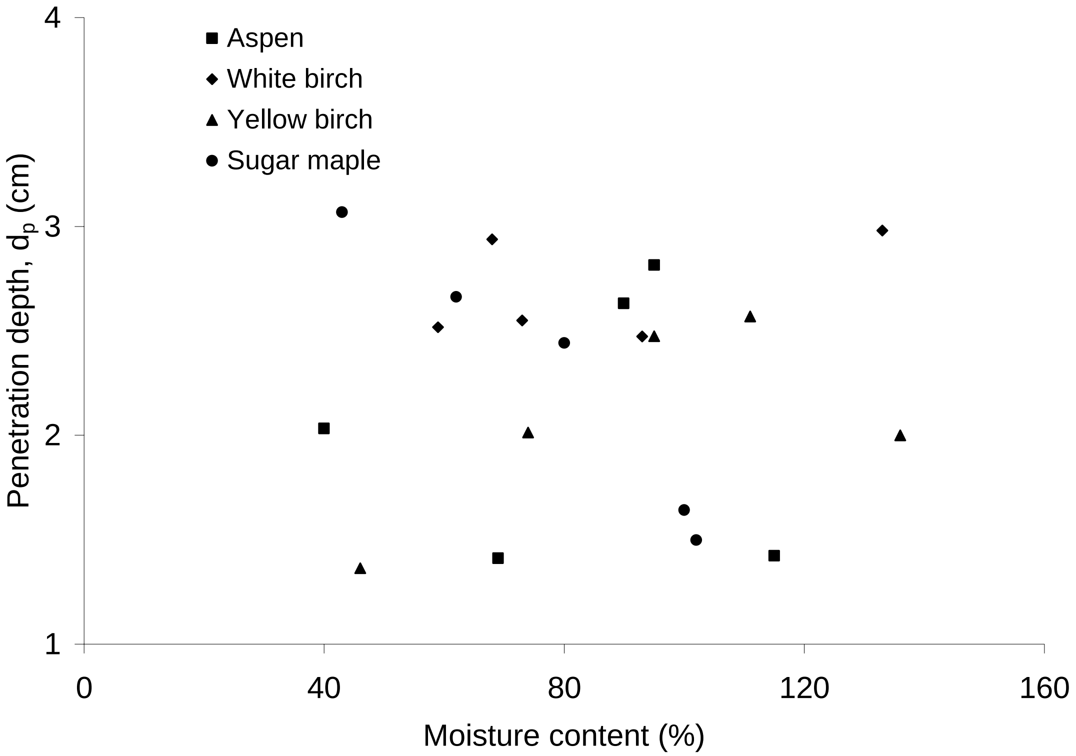

Figure 7: Variation of the penetration depth (d_p) of aspen, white birch, yellow birch and sugar maple as a function of moisture content measured at constant temperature (24 °C) and frequency (2.47 GHz).

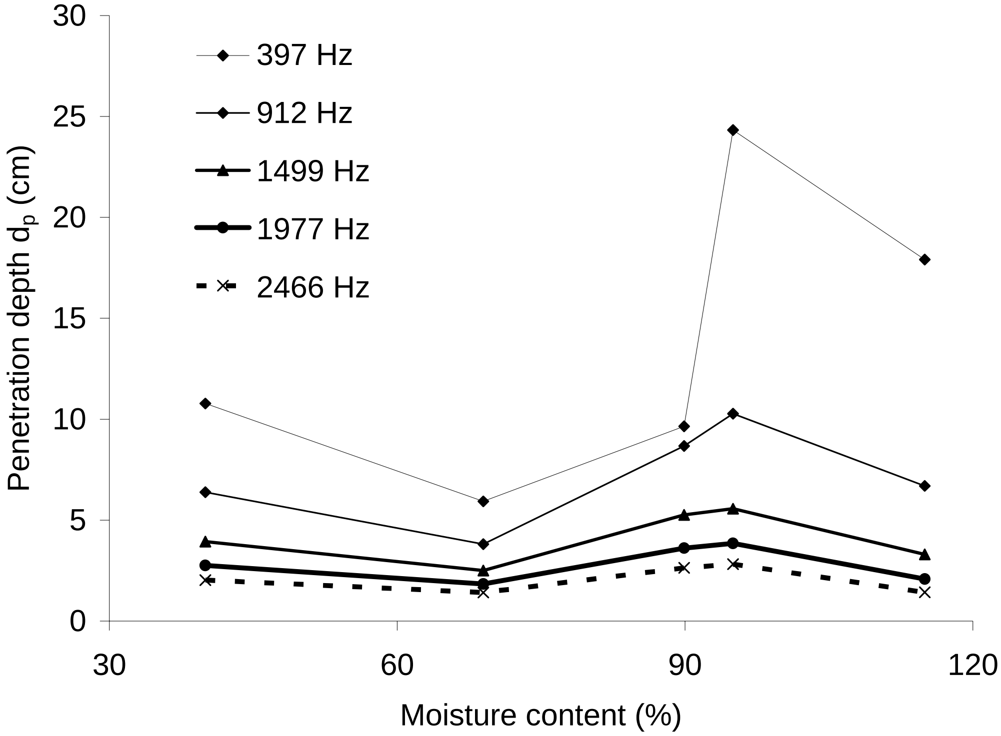

Figure 8: Variation of the half power depth of aspen measured at constant temperature (24 °C) as a function of moisture content and microwave frequency.

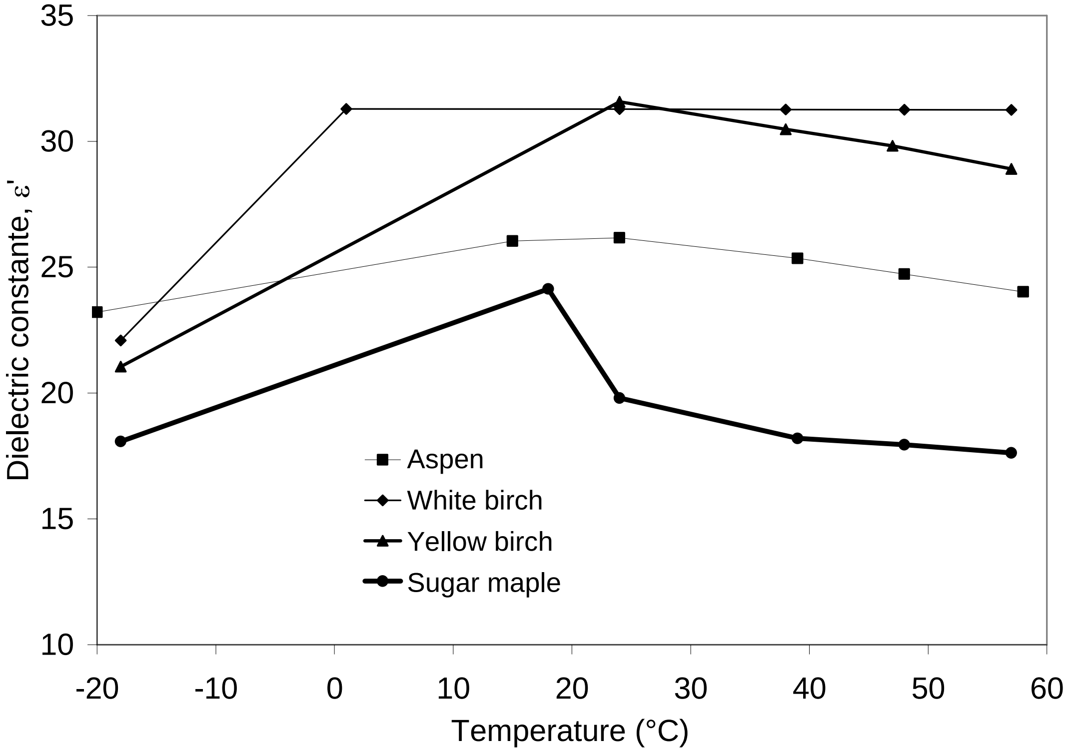

Figure 10: Variation of the dielectric constant (ε’) with species and temperature at constant moisture contents and constant microwave frequency of 2.47 MHz.

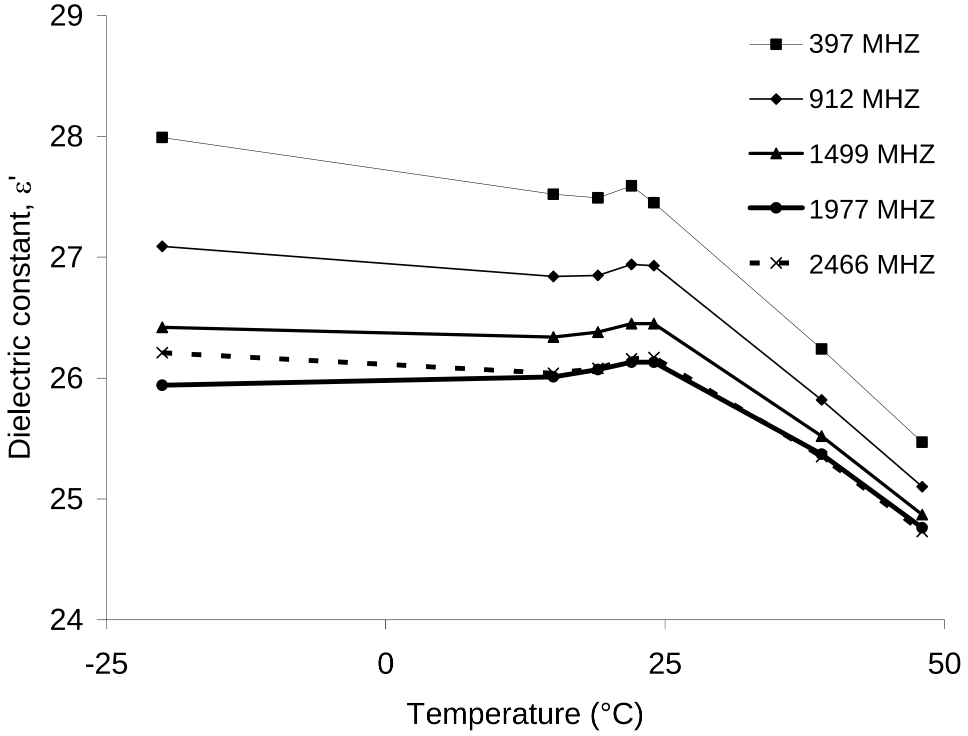

Figure 10: Variation of the dielectric constant ε’ of aspen with temperature and microwave frequency at a constant moisture content of 115%.

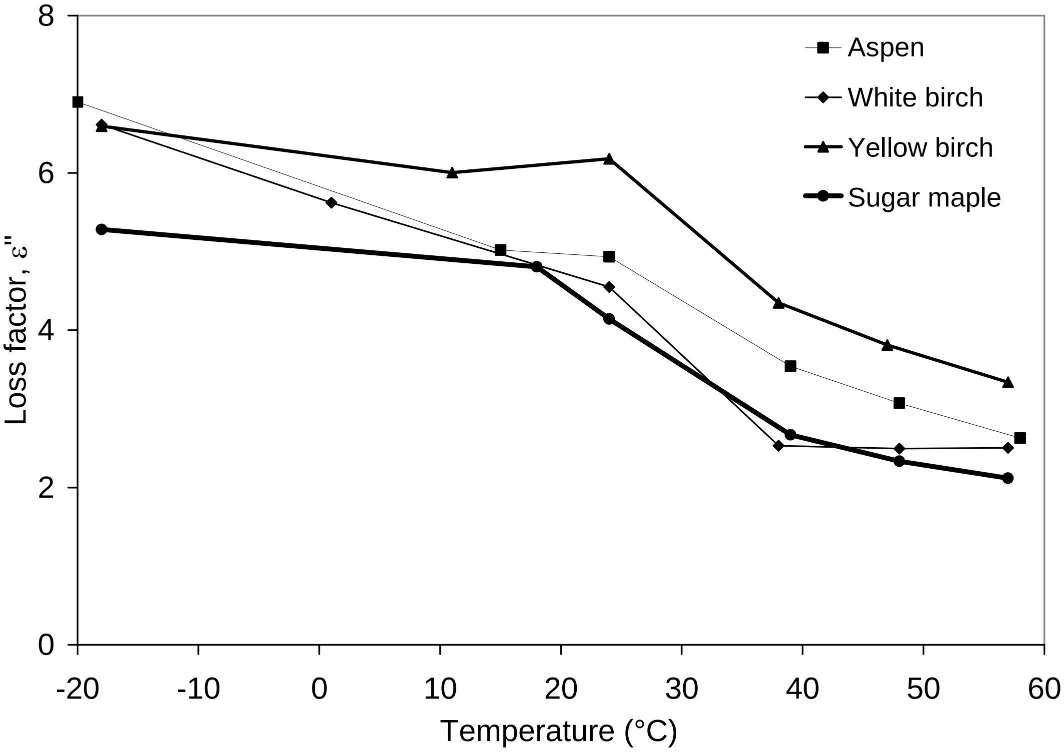

Figure 11: Variation of the loss factor (ε”) with species and temperature at constant moisture content and microwave frequency (2.47 MHz).

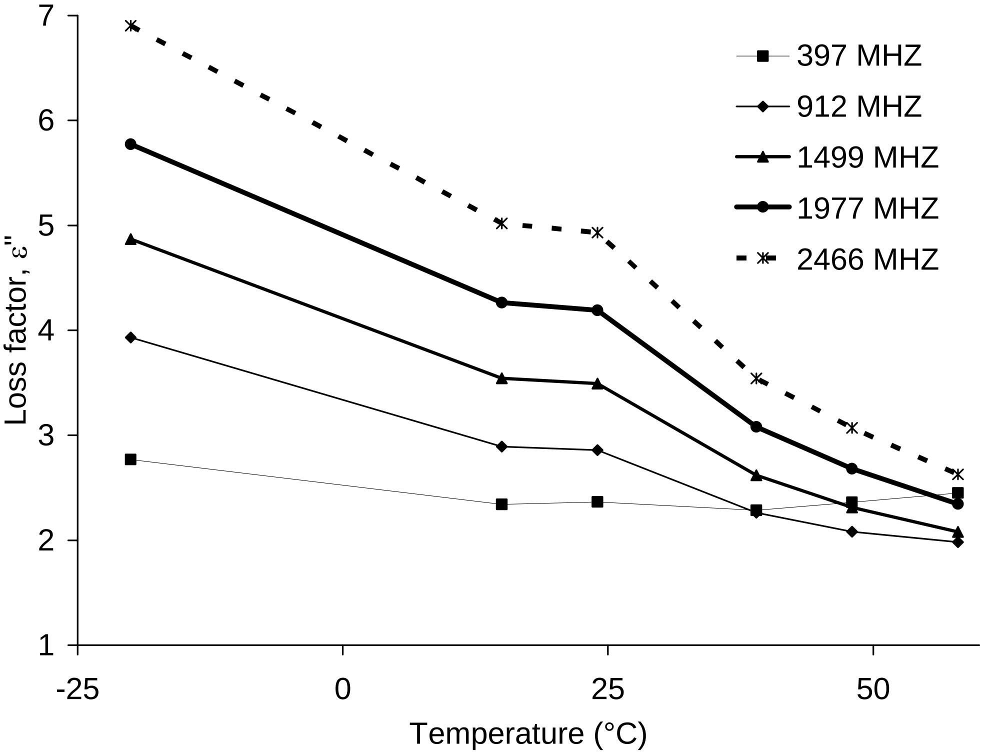

Figure 12: Variation of the loss factor (ε”) of aspen with temperature and microwave frequency at constant moisture content (115%).

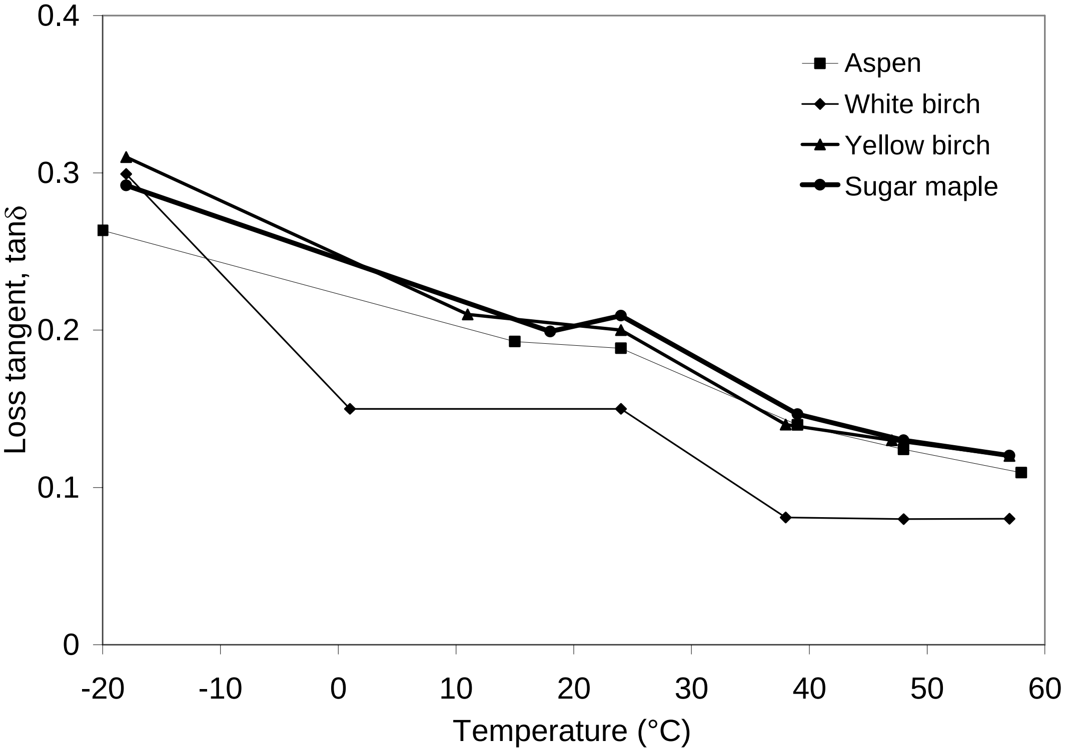

Figure 13: Variation of the loss factor (ε”) with species and temperature at constant moisture content and microwave frequency (2.47 MHz).

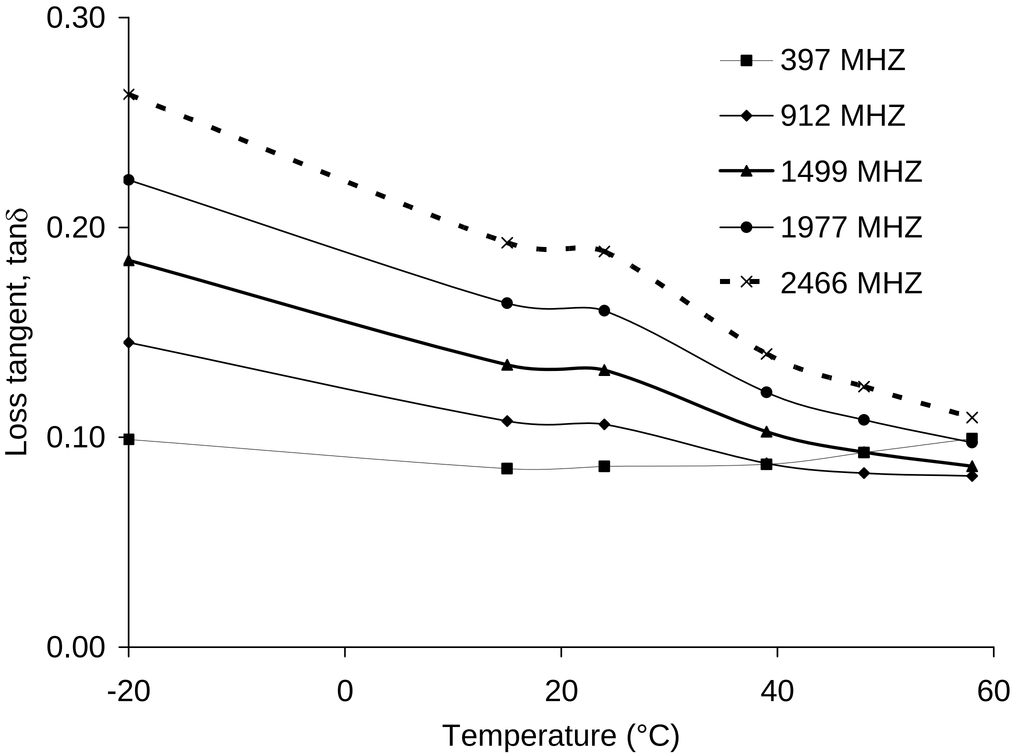

Figure 14: Variation of the loss tangent (tanδ) of aspen with temperature and microwave frequency at constant moisture content (115%).

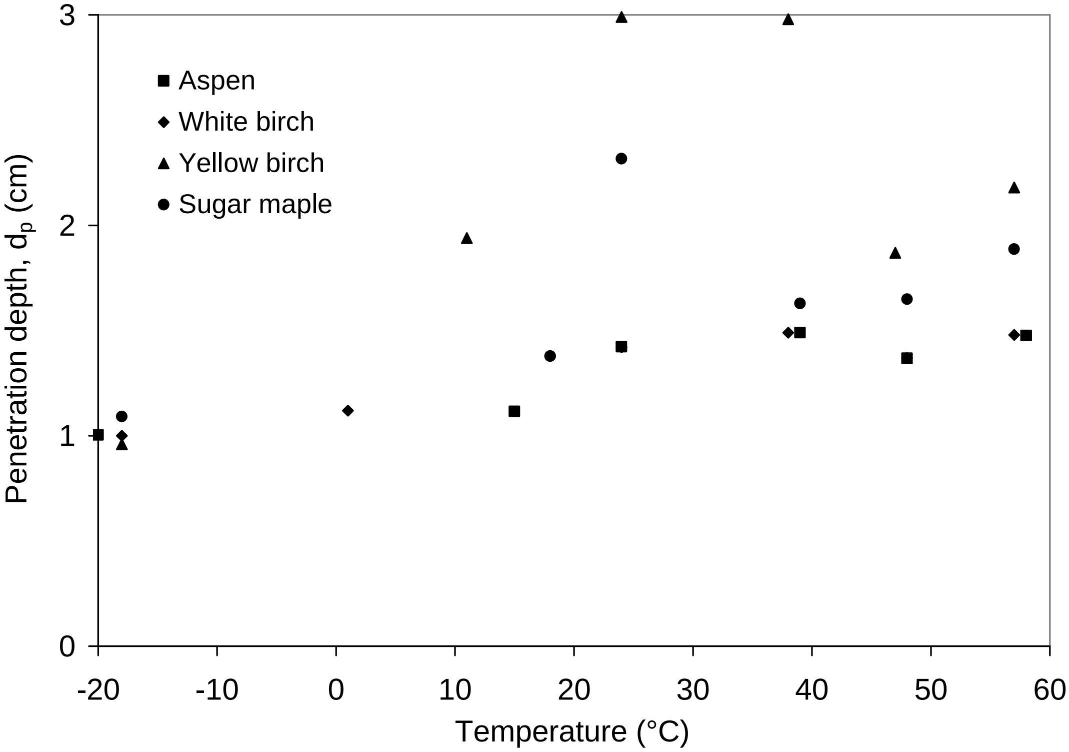

Figure 15: Variation of the penetration depth (d_p) with species and temperature at constant moisture content and microwave frequency (2.47 MHz).

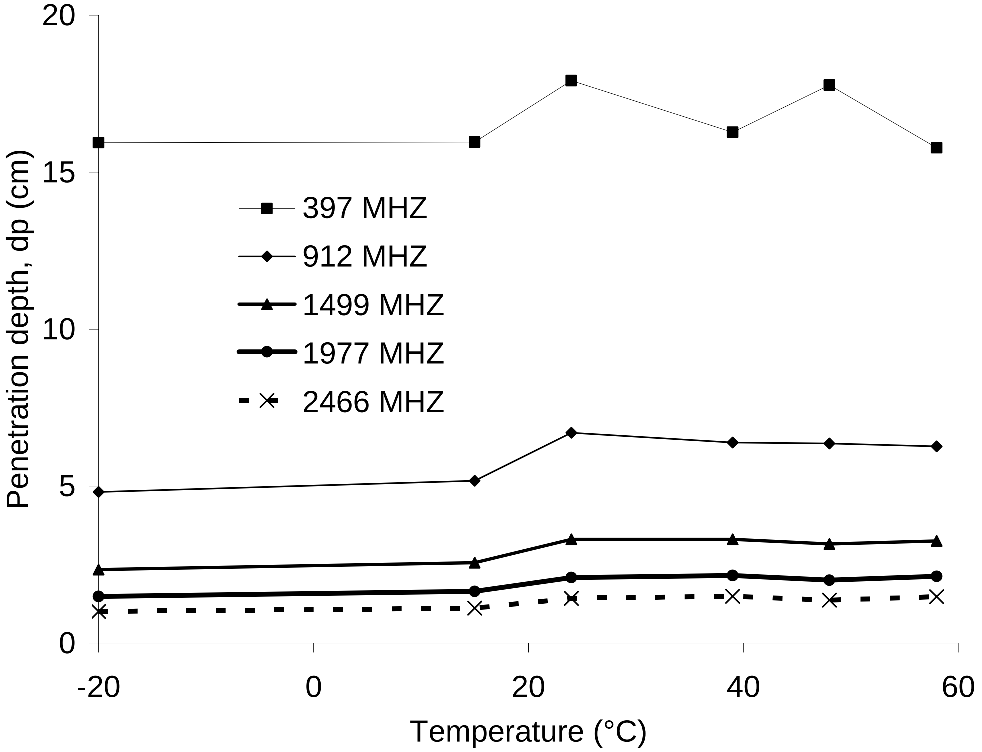

Figure 16: Variation of the loss tangent (tanδ) of aspen with temperature and microwave frequency at constant moisture content (115%).

Legend for Figures:

Figure 1: Mean Power Density of each single board as a function of Moisture Content computed for a stack of 8-boards : Radio-Frequency heating, 40 independent runs with stochastic variation of MC of each board. (adapted from [26]). The general trend of this plot has to be explained by the cumulative effect of ε' and ε''.

Figure 2: Variation of the dielectric constant of aspen, white birch, yellow birch and sugar maple as a function of moisture content, measured at constant temperature (25 °C) and frequency 2.47 (GHz).

Figure 3: Variation of the dielectric constant measured at constant temperature (24 °C) for aspen as a function of moisture content and microwave frequency.

Figure 4: Variation of the loss factor (ε”) of aspen, white birch, yellow birch and sugar maple as a function of moisture content measured at constant temperature (25 °C) and frequency (2.47 GHz).

Figure 5: Variation of the loss factor (ε”) of aspen measured at constant temperature as a function of moisture content and microwave frequency.

Figure 6: Variation of the loss tangent (tanδ) of aspen, white birch, yellow birch and sugar maple as a function of moisture content measured at constant temperature (25 °C) and frequency (2.47 GHz).

Figure 7: Variation of the loss tangent (tanδ) of aspen as a function of moisture content and microwave frequency.

Figure 8: Variation of the penetration depth (dp) of aspen, white birch, yellow birch and

sugar maple as a function of moisture content measured at constant temperature (24 °C) and frequency (2.47 GHz).

Figure 9: Variation of the half power depth of aspen measured at constant temperature (24 °C) as a function of moisture content and microwave frequency.

Figure 10: Variation of the dielectric constant (ε’) with species and temperature at constant moisture content and constant microwave frequency of 2.47 MHz.

Figure 11: Variation of the dielectric constant ε’ of aspen with temperature and microwave frequency at a constant moisture content of 115%.

Figure 12: Variation of the loss factor (ε”) with species and temperature at constant moisture content and microwave frequency (2.47 MHz).

Figure 13: Variation of the loss factor (ε”) of aspen with temperature and microwave frequency at constant moisture content (115%).

Figure 14: Variation of the loss factor (ε”) with species and temperature at constant moisture content and microwave frequency (2.47 MHz).

Figure 15: Variation of the loss tangent (tanδ) of aspen with temperature and microwave frequency at constant moisture content (115%).

Figure 16: Variation of the penetration depth (dp) with species and temperature at constant moisture content and microwave frequency (2.47 MHz).

Figure 17: Variation of the loss tangent (tanδ) of aspen with temperature and microwave frequency at constant moisture content (115%).

Legend for Tables

Table 1: Wood temperature, moisture content and density during testing sequences

Table 2: Dielectric properties as a function of wood species, and moisture content and microwave frequency

Table 3: Dielectric properties as function of wood species, temperature and microwave frequency.

Table 4: Simple Linear models for the relationship between dielectric constant and moisture content

Table 1: Wood temperature, moisture content and density during testing sequences

Species	Test sequence	Temperature range	Moisture content range	Density (D_h)* range
Aspen	1	-20 °C to 85 °C	115 % to 95%	0.76 g/cm^3 to 0.68 g/cm^3
	2	20 °C to 85 °C	90 % to 69%	0.67 g/cm^3 to 0.59 g/cm^3
	3	-20 °C to 85 °C	57 % to 40%	0.55 g/cm^3 to 0.49 g/cm^3
White birch	1	-20 °C to 85 °C	133% - 59%	0.83 g/cm^3 to 0.57 g/cm^3
	2	24 °C to 85 °C	93%-73 %	0.69 g/cm^3 to 0.62 g/cm^3
	3	24 °C to 85 °C	68%-49 %	0.61 g/cm^3 to 0.54 g/cm^3
Yellow birch	1	-20 °C to 85 °C	136 % to 111%	0.86 g/cm^3 to 0.77 g/cm^3
	2	24 °C to 85 °C	102 % to 79%	0.67 g/cm^3 to 0.59 g/cm^3
	3	24 °C to 85 °C	74 % to 46%	0.58 g/cm^3 to 0.49 g/cm^3
Sugar maple	1	-20 °C to 85 °C	123 % to 102%	0.74 g/cm^3 to 0.68 g/cm^3
	2	20 °C to 85 °C	90 % to 70%	0.65 g/cm^3 to 0.55 g/cm^3
	3	20 °C to 85 °C	62 % to 43%	0.56 g/cm^3 to 0.49 g/cm^3

Table 2: Dielectric properties as a function of wood species, and moisture content and microwave frequency

MC	397MHz				912MHz				1499 MHz				1977MHz				2466 MHz			
(%)	ε'	ε"	Tangδ	dp	ε'	ε"	Tangδ	dp	ε'	ε"	Tangδ	dp	ε'	ε"	Tangδ	dp	ε'	ε"	Tangδ	dp
Tembling aspen (*Populus tremuloides)*																				
0	2.05	0.15	0.07		1.95	0.13	0.06		1.90	0.12	0.06		1.90	0.12	0.06		1.83	0.11	0.06	
40	10.8	1.77	0.24	10.78	10.2	1.79	0.18	6.38	9.8	2.00	0.18	3.94	9.5	2.17	0.2	2.76	9.37	2.37	0.25	2.03
69	17	2.09	0.17	5.93	16.2	2.23	0.11	3.80	15.8	2.56	0.1	2.50	15.4	2.92	0.1	1.84	15.4	3.28	0.21	1.41
90	22.3	2.34	0.12	9.65	21.4	2.71	0.09	8.68	20.9	3.21	0.09	5.26	20.5	3.75	0.1	3.62	20.5	4.37	0.21	2.63
95	26.6	2.76	0.09	24.32	25.8	3.02	0.09	10.28	25.2	3.56	0.11	5.56	24.8	4.18	0.12	3.85	24.7	4.86	0.20	2.81
115	25.5	2.36	0.09	17.91	26.9	2.86	0.10	6.70	26.5	3.49	0.13	3.31	26.1	4.19	0.16	2.08	26.2	4.93	0.19	1.42
White birch (*Betula paperyfera)*																				
59	15	2.44	0.16	14.76	14.4	2.3	0.16	6.53	14	2.5	0.18	3.56	13.8	2.77	0.2	2.34	13.3	2.52	0.19	2.52
68	13.2	1.99	0.15	9.81	12.7	1.92	0.15	6.81	12.4	2.1	0.17	4.76	12.2	2.32	0.19	3.71	16.9	2.82	0.17	2.94
73	18.4	2.39	0.13	10.23	18.4	2.35	0.13	6.86	17.9	2.63	0.15	4.51	17.7	3.03	0.17	3.31	17.7	3.45	0.19	2.55
93	21.5	2.15	0.1	9.23	21.1	2.47	0.1	5.49	20.9	2.92	0.14	3.40	20.9	3.44	0.16	2.40	21.1	4.02	0.19	2.47
133	31.2	3.41	0.11	13.68	31.1	3.56	0.11	5.69	30.6	4.11	0.13	2.98	30.1	4.84	0.16	1.92	31.3	4.55	0.15	2.98
Yellow birch *(Betula alleghaniensis)*																				
46	12.2	2.34	0.19	12.38	11.6	2.1	0.18	5.60	11.2	2.23	0.2	3.08	10.9	2.42	0.22	2.02	11	2.68	0.24	1.36
74	14.6	2.13	0.15	13.47	14	2.18	0.16	6.91	13.6	2.42	0.18	4.03	13.3	2.73	0.21	2.80	13.4	3.11	0.23	2.01
95	19.9	3.01	0.15	7.22	19.4	2.86	0.15	5.40	19.1	3.14	0.16	4.04	18	3.63	0.2	3.27	18.5	4.4	0.24	2.47
111	28.2	3.67	0.13	7.64	22.3	3.49	0.16	5.54	22.2	3.9	0.18	4.06	27.6	4.64	0.17	3.23	27.6	5.41	0.2	2.57
136	31.7	3.24	0.1	7.04	26.9	3.56	0.13	4.96	26.4	4.2	0.16	3.51	31.3	5.15	0.16	2.67	31.6	6.18	0.2	2.00
Sugar maple (*Acer saccharum*)																				
43	10.5	1.78	0.17	8.33	9.94	1.73	0.17	6.27	9.62	1.87	0.19	4.68	9.37	2.02	0.22	3.72	9.26	2.18	0.24	3.07
62	13.7	1.96	0.14	12.06	13	2.1	0.16	7.47	12.6	2.34	0.19	4.85	12.4	2.6	0.21	3.49	12.2	2.87	0.23	2.66
80	18.2	2.7	0.15	13.95	17.8	2.52	0.14	7.72	17.4	2.75	0.16	4.64	17.4	3.09	0.18	3.26	17	3.41	0.2	2.44
100	19.9	2.22	0.11	16.79	19.4	2.38	0.12	6.72	19	2.74	0.14	3.52	18.7	3.17	0.17	2.30	18.5	3.54	0.19	1.64
102	22.2	3.42	0.15	11.53	21.8	3.02	0.14	5.62	21.4	3.28	0.15	3.13	21.3	3.69	0.17	2.10	21.2	4.14	0.2	1.50

Table 3: Dielectric properties as function of wood species, temperature and microwave frequency.

T (°C)	397MHz				912MHz				1499 MHz				1977MHz				2466 MHz			
	ε'	ε"	Tangδ	dp	ε'	ε"	Tangδ	dp	ε'	ε"	Tangδ	dp	ε'	ε"	Tangδ	dp	ε'	ε"	Tangδ	dp
Tembling aspen (*Populus tremuloides)*																				
-20	28.0	2.77	0.10	15.9	27.1	3.93	0.15	4.82	26.4	4.87	0.18	2.34	25.9	5.8	0.22	1.49	26.2	6.9	0.26	1.00
15	27.5	2.34	0.09	16.0	26.8	2.89	0.11	5.17	26.3	3.54	0.13	2.56	26.0	4.3	0.16	1.65	26.0	5.0	0.19	1.12
24	27.5	2.36	0.09	17.9	26.9	2.86	0.11	6.70	26.5	3.49	0.13	3.31	26.1	4.2	0.16	2.08	26.2	4.9	0.19	1.42
39	26.2	2.29	0.09	16.3	25.8	2.26	0.09	6.39	25.5	2.62	0.10	3.30	25.4	3.1	0.12	2.15	25.4	3.5	0.14	1.49
48	25.5	2.36	0.09	17.8	25.1	2.08	0.08	6.36	24.9	2.31	0.09	3.16	24.8	2.7	0.11	2.00	24.7	3.1	0.12	1.37
58	24.7	2.45	0.10	15.8	24.3	1.98	0.08	6.26	24.1	2.08	0.09	3.25	24.1	2.3	0.10	2.12	24.0	2.6	0.11	1.48
White birch (*Betula paperyfera)*																				
-18	21.8	2.92	0.13	2.92	21.3	3.73	0.17	3.73	21.1	4.5	0.21	4.5	21.2	5.4	0.25	5.36	22.1	6.6	0.30	1.00
1	32.1	3.39	0.11	3.39	31.6	4.09	0.13	4.09	31.0	4.8	0.16	4.8	30.7	5.6	0.18	5.62	31.3	4.8	0.15	1.12
24	31.2	3.41	0.11	3.41	31.1	3.56	0.11	3.56	30.6	4.1	0.13	4.1	30.5	4.8	0.16	4.84	31.3	4.6	0.15	1.42
38	28.9	3.84	0.13	3.84	28.9	3.11	0.11	3.11	28.7	3.2	0.11	3.2	28.7	3.7	0.13	3.65	31.3	2.5	0.08	1.49
48	28.2	4.21	0.15	4.21	28.1	3.04	0.11	3.04	28.0	3.0	0.11	3.0	28.1	3.2	0.11	3.20	31.3	2.5	0.08	1.37
57	27.5	4.52	0.16	4.52	27.4	3.07	0.11	3.07	27.3	2.8	0.10	2.8	27.4	3.0	0.11	2.95	31.3	2.5	0.08	1.48
Yellow birch *(Betula alleghaniensis)*																				
-18	20.5	2.86	0.14	13.38	20	3.64	0.18	4.51	19.9	4.40	0.22	2.26	20.0	5.3	0.26	1.43	21.1	6.6	0.31	0.96
11	37.6	3.60	0.10	13.95	37.6	5.06	0.13	5.00	37.3	6.29	0.17	2.55	37.5	7.8	0.21	2.62	38.4	8.0	0.21	1.94
24	31.7	3.24	0.10	13.68	26.9	3.56	0.13	5.69	26.4	4.20	0.16	2.98	31.3	5.2	0.16	2.67	31.6	6.2	0.20	2.99
38	30.4	3.69	0.12	18.39	26.9	3.08	0.11	8.49	26.5	3.24	0.12	4.74	30.5	3.8	0.12	1.32	30.5	4.3	0.14	2.98
47	29.6	4.06	0.14	20.61	26.9	3.04	0.11	7.81	26.5	2.99	0.11	4.00	29.8	3.4	0.11	2.63	29.8	3.8	0.13	1.87
57	28.8	4.49	0.16	18.29	25.8	3.04	0.12	8.09	25.5	2.83	0.11	4.39	29.0	3.1	0.11	1.82	28.9	3.3	0.12	2.18
Sugar maple (*Acer saccharum*)																				
-18	17.9	2.45	0.14	14.4	17.5	3.09	0.18	4.93	17.3	3.69	0.21	2.50	17.4	4.4	0.25	1.61	18.1	5.3	0.29	1.09
18	25.1	3.10	0.12	13.5	24.8	3.14	0.13	5.75	24.4	3.58	0.15	3.05	24.2	4.2	0.17	1.98	24.1	4.8	0.20	1.38
24	20.3	3.42	0.17	9.3	20.0	3.02	0.15	6.14	19.9	3.28	0.16	4.09	20.0	3.7	0.18	3.02	19.8	4.1	0.21	2.32
39	19.2	2.35	0.12	13.2	18.8	2.05	0.11	6.09	18.6	2.20	0.12	3.35	18.4	2.4	0.13	2.27	18.2	2.7	0.15	1.63

48	18.8	2.60	0.14	15.8	18.4	2.02	0.11	6.26	18.3	2.04	0.11	3.37	18.2	2.2	0.12	2.28	18.0	2.3	0.13	1.65
57	18.4	2.97	0.16	15.3	18.0	2.06	0.11	6.64	17.9	1.93	0.11	3.69	17.8	2.0	0.11	2.55	17.6	2.1	0.12	1.89

Table 3: Dielectric properties as function of wood species, temperature and microwave frequency.

T (°C)	397MHz				912MHz				1499 MHz				1977MHz				2466 MHz			
	ε'	ε''	Tangδ	dp	ε'	ε''	Tangδ	dp	ε'	ε''	Tangδ	dp	ε'	ε''	Tangδ	dp	ε'	ε''	Tangδ	dp
Tembling aspen (*Populus tremuloides)*																				
-20	28.0	2.77	0.10	15.9	27.1	3.93	0.15	4.82	26.4	4.87	0.18	2.34	25.9	5.8	0.22	1.49	26.2	6.9	0.26	1.00
15	27.5	2.34	0.09	16.0	26.8	2.89	0.11	5.17	26.3	3.54	0.13	2.56	26.0	4.3	0.16	1.65	26.0	5.0	0.19	1.12
24	27.5	2.36	0.09	17.9	26.9	2.86	0.11	6.70	26.5	3.49	0.13	3.31	26.1	4.2	0.16	2.08	26.2	4.9	0.19	1.42
39	26.2	2.29	0.09	16.3	25.8	2.26	0.09	6.39	25.5	2.62	0.10	3.30	25.4	3.1	0.12	2.15	25.4	3.5	0.14	1.49
48	25.5	2.36	0.09	17.8	25.1	2.08	0.08	6.36	24.9	2.31	0.09	3.16	24.8	2.7	0.11	2.00	24.7	3.1	0.12	1.37
58	24.7	2.45	0.10	15.8	24.3	1.98	0.08	6.26	24.1	2.08	0.09	3.25	24.1	2.3	0.10	2.12	24.0	2.6	0.11	1.48
White birch (*Betula paperyfera)*																				
-18	21.8	2.92	0.13	2.92	21.3	3.73	0.17	3.73	21.1	4.5	0.21	4.5	21.2	5.4	0.25	5.36	22.1	6.6	0.30	1.00
1	32.1	3.39	0.11	3.39	31.6	4.09	0.13	4.09	31.0	4.8	0.16	4.8	30.7	5.6	0.18	5.62	31.3	4.8	0.15	1.12
24	31.2	3.41	0.11	3.41	31.1	3.56	0.11	3.56	30.6	4.1	0.13	4.1	30.5	4.8	0.16	4.84	31.3	4.6	0.15	1.42
38	28.9	3.84	0.13	3.84	28.9	3.11	0.11	3.11	28.7	3.2	0.11	3.2	28.7	3.7	0.13	3.65	31.3	2.5	0.08	1.49
48	28.2	4.21	0.15	4.21	28.1	3.04	0.11	3.04	28.0	3.0	0.11	3.0	28.1	3.2	0.11	3.20	31.3	2.5	0.08	1.37
57	27.5	4.52	0.16	4.52	27.4	3.07	0.11	3.07	27.3	2.8	0.10	2.8	27.4	3.0	0.11	2.95	31.3	2.5	0.08	1.48
Yellow birch *(Betula alleghaniensis)*																				
-18	20.5	2.86	0.14	13.38	20	3.64	0.18	4.51	19.9	4.40	0.22	2.26	20.0	5.3	0.26	1.43	21.1	6.6	0.31	0.96
11	37.6	3.60	0.10	13.95	37.6	5.06	0.13	5.00	37.3	6.29	0.17	2.55	37.5	7.8	0.21	2.62	38.4	8.0	0.21	1.94
24	31.7	3.24	0.10	13.68	26.9	3.56	0.13	5.69	26.4	4.20	0.16	2.98	31.3	5.2	0.16	2.67	31.6	6.2	0.20	2.99
38	30.4	3.69	0.12	18.39	26.9	3.08	0.11	8.49	26.5	3.24	0.12	4.74	30.5	3.8	0.12	1.32	30.5	4.3	0.14	2.98
47	29.6	4.06	0.14	20.61	26.9	3.04	0.11	7.81	26.5	2.99	0.11	4.00	29.8	3.4	0.11	2.63	29.8	3.8	0.13	1.87
57	28.8	4.49	0.16	18.29	25.8	3.04	0.12	8.09	25.5	2.83	0.11	4.39	29.0	3.1	0.11	1.82	28.9	3.3	0.12	2.18
Sugar maple (*Acer saccharum*)																				
-18	17.9	2.45	0.14	14.4	17.5	3.09	0.18	4.93	17.3	3.69	0.21	2.50	17.4	4.4	0.25	1.61	18.1	5.3	0.29	1.09
18	25.1	3.10	0.12	13.5	24.8	3.14	0.13	5.75	24.4	3.58	0.15	3.05	24.2	4.2	0.17	1.98	24.1	4.8	0.20	1.38
24	20.3	3.42	0.17	9.3	20.0	3.02	0.15	6.14	19.9	3.28	0.16	4.09	20.0	3.7	0.18	3.02	19.8	4.1	0.21	2.32

39	19.2	2.35	0.12	13.2	18.8	2.05	0.11	6.09	18.6	2.20	0.12	3.35	18.4	2.4	0.13	2.27	18.2	2.7	0.15	1.63
48	18.8	2.60	0.14	15.8	18.4	2.02	0.11	6.26	18.3	2.04	0.11	3.37	18.2	2.2	0.12	2.28	18.0	2.3	0.13	1.65
57	18.4	2.97	0.16	15.3	18.0	2.06	0.11	6.64	17.9	1.93	0.11	3.69	17.8	2.0	0.11	2.55	17.6	2.1	0.12	1.89

Table 4: Simple Linear models for the relationship between dielectric constant and moisture content

Species	Specific gravity	Linear Model	R^2
Tembling aspen *(Populus tremuloides)*	0.37	MC = 0.24ε' - 0.25	0.96
White birch *(Betula paperyfera)*	0.38	MC = 0.22ε' + 1.38	0.99
Yellow birch (*Betula alleghaniensis*)	0.39	MC = 0.22ε' + 0.35	0.95
Sugar maple *(Acer saccharum)*	0.42	MC = 0.18ε' +1.63	0.96
All species		MC = 0.22ε' + 0.61	0.96